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Effective Lagrangian Study of $\gamma p \to K^+\Lambda$ (Spin 3/2 Resonances and Their Off-Shell Effects)

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Abstract

The purpose of the present discussion is to supplement the talk, by B. Saghai at this workshop, on the study of the electromagnetic production of strangeness on the nucleon based upon effective Lagrangian methods. Here we focus on the proper treatment of the spin 3/2 resonances and their associated effects due to the spin 1/2 component of the corresponding fields when they are *off the mass shell*.

1. Introduction

To date, in most works exploiting the effective Lagrangian approach to investigate the photo- (and electro-) production of strangeness on the nucleon, one includes only the tree level contributions consisting of the s-channel nucleon and its excited resonant state exchanges, the u-channel hyperonic resonance exchanges, and a few t-channel strange meson exchanges. Note that this is also known as the *isobar* approximation. As the s-channel incident photon energy becomes higher, the more massive baryonic resonances with spin higher than 1/2 need to be included in this scheme. Until recently, the inclusion of higher spin resonances had never been exercised except in

the work of Renard and Renard [1] in the early 70's. However, this work did not recognise the propagation of the spin 1/2 components of the Rarita-Schwinger spin 3/2 field *off-shell*. A recent approach [2] took a somewhat different point of view and included spin 3/2 and 5/2 resonances, but only in the s-channel due to an unwanted singularity in the u-channel arising from an approximate treatment of these higher spin objects while respecting gauge invariance.

A proper spin 3/2 resonance treatment was discussed [3] and exploited by the Rensselaer Polytechnic (RPI) group for the photo- (electro-) production of the pion in the $\Delta(1232)$ resonance region [4]. In what follows we shall extend their approach to K-meson production. Our result in the

$$\gamma^{(*)}p \to K^+\Lambda$$

reaction has recently been published in [5] and the details can be found therein. In the present discussion we shall include one additional aspect in its yet exploratory stage, but not investigated in [5].

2. Spin 3/2 Resonances and Their Off-shell Effects

First, we refer the reader to appropriate articles on the proper treatment of spin 3/2 fields for more detail [3, 6, 7].

Following the convention found in Bjorken and Drell [8], we write the spin 3/2 (isospin 1/2 for our present discussion) Rarita-Schwinger [vector-spinor field] (resonance) as R^μ. Without interaction this field should obey the free Dirac equation (with M_R: the mass of the resonance)

$$(i\partial\!\!\!/ - M_R)R^\mu = 0, \tag{1}$$

with the subsidiary condition to be satisfied by the *on-shell* spin 3/2 resonance:

$$\gamma_\mu R^\mu = 0 \tag{2}$$

ensuring the correct number of spin components. (The often mentioned additional condition: $\partial_\mu R^\mu = 0$, is automatically met by the two equations above.) Then the most general form of the corresponding free Lagrangian reads,

$$\mathcal{L}_{\rm free} = \overline{R}^\alpha \Lambda_{\alpha\beta} R^\beta, \tag{3}$$

where

$$\Lambda_{\alpha\beta} = -\Big[(-i\partial\!\!\!/ + M_R)g_{\alpha\beta} - iA(\gamma_\alpha\partial_\beta + \gamma_\beta\partial_\alpha) - \frac{i}{2}(3A^2+2A+1)\gamma_\alpha\partial\!\!\!/\gamma_\beta - M_R(3A^2+3A+1)\gamma_\alpha\gamma_\beta\Big]. \tag{4}$$

Here $A(\neq -1/2)$ is a free parameter. Since this Lagrangian can be shown to be invariant under the following point (or contact) transformation

$$R^\mu \to R^\mu + a\gamma^\mu\gamma^\nu R_\nu; \quad A \to A + (A-2a)/(1+4a), \tag{5}$$

($a \neq -1/4$, but otherwise arbitrary), observables resulting from this Lagrangian is free of parameter A. Note that on the right hand side of the above transformation for R^μ, the part proportional to $\gamma^\nu R_\nu$ may be easily seen to behave as a Dirac spin 1/2 field. Thus *off the mass shell* the Rarita-Schwinger field R^μ is always mixed with spin 1/2 components. This has an important bearing on what we are going to discuss in the following.

First, the propagator for the R^μ field is the inverse of $\Lambda_{\mu\nu}$, and its simplest form may be found by setting $A = -1$,

$$P_{\mu\nu}(q) = \frac{q\!\!\!/ + M_R}{3(q^2 - M_R^2)}\left[3g_{\mu\nu} - \gamma_\mu\gamma_\nu - \frac{2q_\mu q_\nu}{M_R^2} - \frac{q_\nu\gamma_\mu - q_\mu\gamma_\nu}{M_R}\right], \tag{6}$$

where q is the four momentum of the resonance. It is important to note [3] that this propagator describing the on- and off-shell propagation of the spin 3/2 resonance contains a spin 1/2 contribution: only at the pole of the propagator (the on-shell point) does the spin 1/2 contribution vanish and only the pure spin 3/2 component retained. It has been shown that dropping the spin 1/2 component would lead to a propagator with no inverse [3].

Next, the interactions associated with the spin 3/2 field R^μ which respects the invariance under the point transformation of the free Lagrangian must be of the form: $\mathcal{L}_I = j^\mu\Theta_{\mu\nu}R^\nu + h.c.$, where the most general form for Θ was found to be [6, 9]

$$\begin{aligned}\Theta_{\mu\nu}(V) &= (g_\mu^\alpha + V\gamma_\mu\gamma^\alpha)(g_\nu^\alpha + A/2\cdot\gamma^\alpha\gamma_\nu) \\ &\to g_{\mu\nu} - (V+1/2)\gamma_\mu\gamma_\nu \qquad (A=-1).\end{aligned} \tag{7}$$

Here V is a free parameter, and while the physical quantities are independent of A, as the full Lagrangian is invariant under the point transformation [10], they do depend upon V. From the above expression one sees that V enters to modify only the spin 1/2 part of the Rarita-Schwinger field. Hence, it is clear that the spin 3/2 resonance pole part of the amplitudes is independent of V. For this reason V is called the *Off-Shell Parameter*. Our objective then is to study the effect of these off-shell degrees of freedom on the electromagnetic production of strangeness on the nucleon. Note that this cannot be done consistently while using an inappropriate resonance propagator which ignores the spin 1/2 contribution. Since our spin 3/2 fields are not elementary but composites of more fundamental constituents, the corresponding off-shell parameters should not be fixed to definite values: a point of view adopted by [3].

Our phenomenological interaction Lagrangian consists of the following pieces:

$$\mathcal{L}_{K\Lambda R} = \frac{g_{K\Lambda R}}{M_K}\left[\overline{R}^{\nu}\Theta_{\nu\mu}(Z)\Lambda\partial^{\mu}K + \overline{\Lambda}(\partial^{\mu}K^{\dagger})\Theta_{\mu\nu}(Z)R^{\nu}\right], \tag{8}$$

$$\mathcal{L}^{(1)}_{\gamma pR} = \frac{ieg_1}{2M_p}\left[\overline{R}^{\nu}\Theta_{\mu\lambda}(Y)\gamma_{\nu}\gamma^5 NF^{\nu\lambda} + \overline{N}\gamma^5\gamma_{\nu}\Theta_{\lambda\mu}(Y)R^{\mu}F^{\nu\lambda}\right], \tag{9}$$

$$\mathcal{L}^{(2)}_{\gamma pR} = \frac{-eg_2}{4M_p^2}\left[\overline{R}^{\mu}\Theta_{\mu\nu}(X)\gamma^5(\partial_{\lambda}N)F^{\nu\lambda} - (\partial_{\lambda}\overline{N})\gamma^5\Theta_{\nu\mu}(X)R^{\mu}F^{\nu\lambda}\right], \tag{10}$$

$$\mathcal{L}^{(3)}_{\gamma pR} = \frac{-eg_3}{4M_p^2}\left[\overline{R}^{\mu}\Theta_{\mu\nu}(W)\gamma^5 N(\partial_{\lambda}F^{\nu\lambda}) - (\partial_{\lambda}F^{\nu\lambda})\overline{N}\gamma^5\Theta_{\nu\mu}(W)R^{\mu}\right]. \tag{11}$$

The above expression may be found in [5] except for the last piece, the necessity of which has been communicated to us by Rick Davidson [11]. This part contributes only to the electroproduction process, which may be obvious from the presence of the divergence of the electromagnetic tensor $F^{\nu\lambda}$ in the interaction: classically this quantity vanishes when there is no source for electric charge/current.

3. Result and Discussion

With the introduction of the spin 3/2 resonances as discussed above, we constructed the tree level amplitude for $\gamma^{(*)}p \to K^+\Lambda$, and performed a χ^2

fit to the existing data in which the coupling strengths of the intermediate resonances (to the initial and final states, in combination) and the off-shell parameters: W, X, Y, Z were varied.

The result without the $\mathcal{L}^{(3)}_{\gamma pR}$ term has been worked out in [5], and the reader is referred to that article for details. In summary, the correct treatment of the spin 3/2 resonances has improved the fit to the existing data. In particular, the undesirable increase in the integrated cross section for $E_\gamma^{Lab} > 1.5$ GeV in previous models ([2], for example) has been considerably tempered, and the large angle differential cross section at $E_\gamma^{Lab} = 2.0$ GeV has changed drastically, in favor of the yet preliminary data from Bonn [12]. Predictions for several polarisation observables both in photo- and electro-productions show a marked difference between the approaches with and without the off-shell considerations in spin 3/2 resonances.

Regarding the off-shell effects arising from the $\mathcal{L}^{(3)}_{\gamma pR}$ term which only affects electroproduction, our preliminary results indicate a rather minor effect: we basically need ample data points to firmly constrain the corresponding parameter(s): coupling strength and the off-shell parameter W.

Incorporating resonances with spin higher than 3/2 is yet to be investigated within the context of covariant schemes.

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